Energy Policy 119 (2018) 502–514

Contents lists available at ScienceDirect

Energy Policy

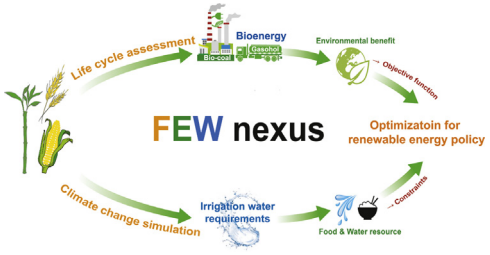
journal homepage: www.elsevier.com/locate/enpol

Spatial optimization of the food, energy, and water nexus: A life cycle assessment-based approach

Kuang-Yu Yuan[a], Ying-Chen Lin[a,b], Pei-Te Chiueh[a,*], Shang-Lien Lo[a]

[a] Graduate Institute of Environmental Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan
[b] Department of Urban Planning and Spatial Information, Feng Chia University, No. 100, Wenhwa Rd., Seatwen, Taichung 40724, Taiwan

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Food, energy and water nexus (FEW nexus)
Life cycle assessment
Renewable energy policy
Climate change
Optimization

ABSTRACT

Since the Bonn 2011 Conference, the Food-Energy-Water (FEW) nexus has become one of the most popular global research topics. Understanding and addressing the complex interactions between the FEW components is essential for sustainable development. This study proposes an environmental impact minimization model, which considers the FEW nexus under four climate change scenarios, to optimize the spatial distribution of three energy crops (rice, corn, and sugarcane). Life cycle assessment (LCA), linear programming, and a climate change simulation model are integrated to analyze appropriate bioenergy production rates while comparing the benefits of bioenergy with the current renewable energy policy in Taiwan. The major findings of LCA in this study indicate that electricity generation using bio-coal produced from rice straw is very beneficial to the environment. Considering the spatial characteristics of Taiwan, simulations from the spatial optimization model suggested that (a) the rice and corn cultivation areas should be increased in southern Taiwan for bio-coal and bioethanol production, in accordance with the "food and feed priority policy"; and (b) the rice cultivation area should be decreased across Taiwan, based on the "water conservation policy". In addition, compared to solar power, the development of bioenergy can simultaneously enhance food and energy self-sufficiency.

1. Introduction

As population growth and major socioeconomic changes lead to growing demand for vital services and resources, energy, food, and water security are becoming increasingly important (FAO, 2009; IEA, 2015; Mountford, 2011). However, the absence of systematic management of water, energy, and food makes it more difficult to balance the rising demand for these resources. To improve resource efficiency, the concept of the food, energy, and water (FEW) nexus has gained significant attention, as it is important for the well-being of mankind and the environment (Ringler et al., 2013).

A few researches have been undertaken on the food-energy linkage (Alfonso et al., 2009; Hatirli et al., 2006; Pahlavan et al., 2012; Pishgar-Komleh et al., 2011; Safa and Samarasinghe, 2011), the food-water

* Corresponding author.
E-mail address: ptchueh@ntu.edu.tw (P.-T. Chiueh).

https://doi.org/10.1016/j.enpol.2018.05.009
Received 11 October 2017; Received in revised form 14 April 2018; Accepted 4 May 2018
Available online 23 May 2018
0301-4215/ © 2018 Elsevier Ltd. All rights reserved.

linkage (Chiang et al., 2015; Holland et al., 2015; Motoshita et al., 2014; Pfister et al., 2011; Tuong et al., 2005; Wu et al., 2012), and the water-energy linkage (Brennan and Owende, 2010; Gerbens-Leenes et al., 2009; Hagman et al., 2013; Hermann et al., 2012; Mo et al., 2014; Siddiqi and Anadon, 2011). In order to comprehensively integrate the assessment of these linkages, Al-Ansari (2016) proposed a systematic tool which combines industrial ecology and life cycle assessment (LCA), to quantify material flows and energy consumption, and identify environmental pressures within the FEW nexus. Al-Ansari et al. (2014) characterized the relationship between each part of the FEW nexus, introducing a renewable energy generation system, which uses biomass as the feedstock, to enhance environmental performance. Bazilian et al. (2011) identified the inter-relationship between food, energy, and water security, highlighting the importance of biofuel production and irrigation water within the nexus. Steubing et al. (2012) proposed an optimization approach to assess food, bioenergy, and water resource use efficiency.

Electricity generated from bioenergy can be a practical option to achieve short-term greenhouse gas (GHG) emission reductions, where the technology allowing for co-firing of biomass with coal in existing coal-fired plants is sufficiently advanced (OECD and IEA, 2015). Biofuel plays an important role in enhancing energy security and reducing GHG emissions in the transport sector (IEA, 2011). The use of bioenergy from biomass can not only mitigate the stress of fossil-energy requirements but also decrease life cycle GHG emissions. Murphy and McDonnell (2017) indicated that indigenous sources of biomass for co-firing systems have lower GHG emission profiles than imported biomass, highlighting the importance of further research on biomass sources in the agricultural and food sectors.

In addition, the integration of LCA and geographic information system (GIS) can allow for comprehensive evaluation for sustainable bioenergy planning (Hiloidhari et al., 2017). Both Monforti et al. (2013) and Haase et al. (2016) estimated the potential of agro-residues for bioenergy production in the European Union using GIS. Considering the environmental characteristics, availability, and distribution of agro-residues, GIS aids in analyzing the spatiotemporal database to source and collect raw materials effectively and to allocate the benefits of bioenergy (Long et al., 2013). Selection of agricultural residues for bioenergy production can prevent competition with food production over land resources, thus aligning with sustainable development (EU, 2009). Bioenergy production from food waste and residual biomass could supply an enormous part of the energy demand of the food system, eventually becoming a development target.

One critical challenge faced by renewable energy is that its production is influenced by unmanageable weather conditions and noticeable climate change (Wang et al., 2016). For instance, weather patterns affect wind power and solar energy generation systems, while long-term climate change influences bioenergy production. Previous studies have discussed the impacts of climate change on water resources and food production (Tung et al., 2013), although little emphasis was placed on the energy part of the nexus. Criqui and Mima (2012) emphasized the consequences of climate change from the energy dimension, based on different degrees of GHG emission constraints and European climate policy. They indicated that stringent environmental policies might benefit the development of a more climate-friendly energy model, thus reducing the vulnerability of the energy market to potential price or supply fluctuations.

This study proposes a spatial optimization model for the FEW nexus analyzing the tradeoffs between food production, bioenergy generation, and environmental impacts, thus providing a better perspective on renewable energy development. The environmental impacts from components of the FEW nexus were examined through LCA, with a special focus on comparing bioenergy and traditional energy sources for generating electricity. The proposed optimization model addresses food, energy, and water security, while simultaneously considering climate factors under the Intergovernmental Panel on Climate Change (IPCC) climate change scenarios. In addition, we analyzed Taiwan's current renewable energy policies and the problems associated with farmland-based solar power systems. Based on this analysis, our study establishes a useful FEW assessment framework for selecting appropriate food, energy, and water policies to satisfy domestic demand while simultaneously mitigating environmental impacts. A case study of rice, corn, and sugarcane, the most common bioenergy crops in Taiwan (Chen et al., 2011a, 2011b; Tsai, 2014), was used to determine the optimal spatial distribution of crop cultivation areas based on different scenarios. Our results can inform bioenergy development strategies as well as food policy while considering the influence of climate change from an environmental perspective.

2. Methods

2.1. Assessment framework

In this study, two bioenergy products incorporating three agricultural residue feedstocks were selected as the assessment targets for analysis under two FEW nexus policies. The bioenergy products were bio-coal produced from rice straw via torrefaction and cellulosic ethanol produced from corn stover and sugarcane bagasse. The proposed optimization model consists of two main components, as shown in Fig. 1: (1) the objective functions and (2) the constraints. The coefficients of the objective functions were determined by evaluating the environmental impact reduction using LCA. The constraints on the optimization model included analysis of government policies and available water resources simulated from climate change model. The optimal spatial distribution of arable lands for the three crops is displayed in digital maps.

Multiple methods are integrated into this assessment framework. LCA (ISO14040, 2006; ISO14044, 2006) is the preferred method to quantify the environmental impacts, as it has been commonly applied to the agricultural sector worldwide. The influence of climate change on water resources is also considered in the current study through the irrigation water requirements. Although previous studies have focused on the importance of crop production and environmental impacts (Lin et al., 2013), cost-benefit analysis in the bioenergy sector (Rasheed et al., 2016), and the impact of climate change on agriculture (Chang et al., 2012; Chen et al., 2011a, 2011b), much less attention has been paid to identifying optimal strategies for bioenergy production coupled with crop distribution. The proposed optimization model integrates LCA and climate change simulations by comparing alternatives according to national or regional development policies, which can be used to optimize trade-offs between bioenergy production, food supply, and environmental benefits.

2.2. Life cycle assessment (LCA) of bioenergy production

Life cycle assessment is a systematic set of procedures for compiling and examining the inputs and outputs of raw materials and energy associated with environmental impacts through production, usage, and disposal (ISO14040, 2006). In this study, LCA is regarded as a quantitative tool to measure the environmental benefits of energy alternatives by comparing fossil energy production with bioenergy production. Subsequently, the environmental impact reduction resulting from alternative energy use rather than traditional energy sources serve as the decision variables of the objective function in the proposed optimization model. Impact 2002 +, an impact assessment methodology originally developed at the Swiss Federal Institute of Technology (Jolliet et al., 2003), was selected for life cycle impact assessment (LCIA), owing to the advantages offered by the Eco-indicator 99, CML 2001, and Cumulative Energy Demand components. Both mid-point and end-point assessments are incorporated in this methodology.

The assessment boundary for bio-coal generated from rice straw via torrefaction included: (1) rice cultivation; (2) in-situ collection; (3) bio-

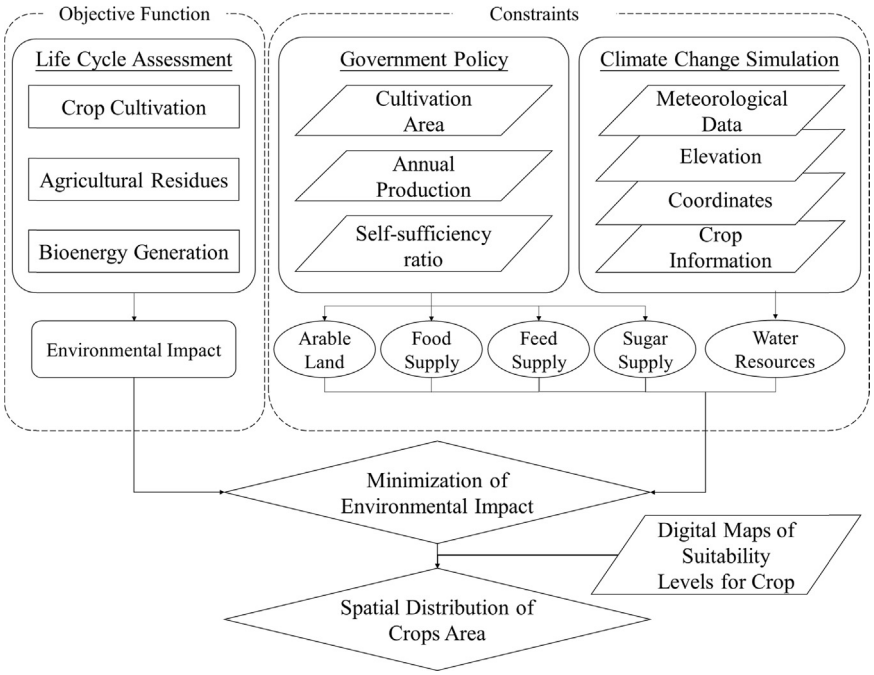


Fig. 1. Proposed assessment framework in this research.

coal production through torrefaction; (4) transportation to the power plant; and (5) electric power generation through firing. The system boundary for gasohol blended with cellulosic ethanol contained: (1) corn or sugarcane cultivation; (2) in-situ crushing and collection; (3) pre-treatment; (4) saccharification and fermentation; (5) distillation and dehydration; and (6) blending with gasoline. The destruction and disposal of farms, plants, and any facilities were excluded from the system boundaries.

2.3. Optimization of crop cultivation area for bioenergy

The optimization goal of this study was to determine the rational spatial distribution for each crop (rice, sugarcane, and corn), and the associated environmental benefits and bioenergy yields. The objective function, which is regarded as the goal of this research, is to minimize the environmental impact associated with food security, green energy, and sustainability. The total area of arable land in 2015 was defined as a constraint, owing to limited land resources. The decision variables were the cultivation areas of rice, sugarcane, and corn.

Table 1 lists the nomenclature used throughout this study. Since the environmental benefits of biofuel use are obtained by comparing biofuel with traditional fuel, the maximum impact reduction achievable is determined as an objective function in this optimization model, using Eq. (1):

$$\text{Max.Impact reduction} = \sum_b \sum_j \sum_i \left\{a_{i,j}\cdot\left[I_{t_b} - (I_i\cdot R_i + I_b)\right]\cdot C_{i,b}\cdot Y_{i,j}\cdot LHV_b\right\} \quad (1)$$

The cultivated areas of crops in distinct regions ($a_{i,j}$) are the decision variables of the objective function, a set of quantities that need to be determined in a linear program. These variables represent the amount of arable land which can be used for each crop. As a comparative basis for impact mitigation, the environmental impact of traditional fuels (I_{t_b}) corresponds to that of the specific bioenergy. This means that bioelectricity corresponds to coal-fired power, while gasohol corresponds to gasoline. Constraints are described in both the text and formulas in the following sections.

Table 1
Nomenclature used in the objective function and constraint formulas.

Legend	Description	Unit
b	Bioenergy (i.e., bioelectricity, gasohol)	
j	Region (i.e., Northern, Central, Southern and Eastern regions)	
i	Crop (i.e., rice, sugarcane, corn)	
$a_{i,j}$	Cultivated area for i crops in j region	ha
I_{t_b}	Environmental impact of t traditional energy (i.e., coal-fired power, gasoline) corresponding to the specific bioenergy b	1/MJ
I_i	Environmental impact caused by i crop cultivation	1/MJ
R_i	Impact allocation rate for i crop to agricultural residues	
I_b	Environmental impact caused by bioenergy conversion	1/MJ
$C_{i,b}$	Conversion rate of i biomass to b biofuel	
$Y_{i,j}$	Yield of i crop in j region	kg/ha
LHV_b	Lower heating value of b biofuel (e.g., bio-coal, cellulosic)	
$A_{i,j}$	Cultivation area of i crop in j region in 2015	ha
r	Relaxation rate in each scenario	
$W_{i,j}$	Irrigation water availability for i crop in j region	m^3/ha
S_{RCP}	Increase rate of irrigation water requirements based on the representative concentration pathway (RCP)	

2.3.1. Hypothetical policies of the FEW nexus

Analysis of the FEW nexus in this research is based on two hypothetical policies with respect to food and water, considered simultaneously under four climate change scenarios, to identify the optimal spatial bioenergy yield and environmental performance. The two hypothetical policies are as described below:

1. Food and feed priority: Rice consumption is estimated to remain nearly constant, with a self-sufficiency ratio (domestic production divided by domestic consumption) not less than 100%. In this scenario, it assumed that the government would increase consideration of food self-sufficiency when developing bioenergy. As such, there are stricter constraints on the minimum food and feed supply, with fewer constraints on the use of water resources.
2. Water conservation: The rice grain water consumption is estimated to decrease continuously. Moreover, this policy aims to reduce the amount of water allocated to the agricultural sector in case of water scarcity. Water resources are considered limited and should not be overly allocated to agriculture and agricultural residue bioenergy.

Table 2
Parameters used in the optimization model.

		2015	Food and feed priority	Water conservation
Constraints				
Max	Total arable land (ha)	189,831	100%	100%
Min	Food supply (10^3 t)	1273	90%	50%
Min	Feed supply (10^3 t)	83	90%	90%
Min	Sugar supply (10^3 t)	1050	100%	100%
Max	Water consumption (10^3 m^3)	7,753,151	according to the simulation of irrigation water requirements	

This policy focuses on increasing water use efficiency in agriculture and other water-intensive industries, such that the upper limit of water consumption is stricter than under the food and feed priority policy scenario.

Both policies have different constraints on resource use, based on distinct settings (Table 2). The details of the constraints are described in the following sections.

2.3.2. Climate change simulation

Climate change scenarios were simulated using the TaiWAP software (Liu et al., 2009; Tung et al., 2014) to estimate changes in precipitation and temperature-related irrigation water requirements. By integrating the assessment system with a weather generator, a general watershed loading function (GWLF), the estimation of irrigation water requirements, and a water resources simulation model, TaiWAP provides comprehensive tools for assessing the impacts of climate change on water resources.

To characterize spatial features, this study divided Taiwan into four regions: northern, central, southern, and eastern, with each region containing three to seven administrative areas (Table 3). The meteorological data, including daily temperature and precipitation from 2000 to 2015 for the Taipei, Taichung, Tainan, and Hualien stations, which represent the northern, central, southern, and eastern regions, respectively, were selected as the baseline for the simulation. The near future (2021–2040) was simulated as the input parameter for water resource assessment.

The lognormal distribution, a continuous probability distribution, was applied to simulate precipitation distribution patterns, based on the four representative concentration pathway (RCP) scenarios provided by the IPCC (2013; Table 4). The variation in monthly precipitation and temperature was also compared with the baseline period for the four scenarios. The general circulation models (GCMs) for climate change simulation were selected following Lin and Tung (2017), with HadGEM2-AO (Martin et al., 2011) used for the northern, southern, and central regions, while CESM1-CAM5 (Kay et al., 2015) was used for the eastern region (Table 4).

2.3.3. Boundary of total arable land

According to the Renewable Energy Directive from the European Commission (EU, 2009), energy crop cultivation cannot be carried out on land with high carbon stocks and high biodiversity. This means biofuel cannot be grown in areas such as wetlands, forests, or highly biodiverse grasslands. Hence, the boundary of the land areas used in the spatial optimization model was equal to the area used for crop cultivation in the baseline year.

$$\sum_j \sum_i a_{i,j} \le \sum_j \sum_i A_{i,j} \quad (2)$$

Table 3
Administrative areas of the four regions.

Region	Administrative areas
Northern	Taipei City, New Taipei City, Taiyuan City, Keelung City, Hsinchu City, Hsinchu County, Miaoli County
Central	Taichung City, Changhua County, Nantou County, Yunlin County, Chiayi City, Chiayi County
Southern	Tainan City, Kaohsiung City, Pingtung County
Eastern	Yilan County, Hualien County, Taitung County

2.3.4. Food supply (rice)

Since it is crucial to meet the basic demand for food, a minimum amount of food production was set as a constraint. The relaxation rate (domestic consumption divided by domestic production) (Callesen et al., 2010) was calculated based on the actual rates of food consumption versus domestic production in Taiwan to prevent food overproduction. In the "food and feed priority policy", a relaxation rate of 90% was selected, while in the "water conservation policy", a relaxation rate of 50% was selected due to high water consumption during rice cultivation.

$$\sum_j (Y_{i,j} \times a_{i,j}) \ge \sum_j Y_{i,j} \times A_{i,j} \times r, \quad (3)$$

where i represents rice, and the relaxation rate (r) can be changed for different FEW policies.

2.3.5. Feed supply (corn)

Since domestic feed production for livestock in Taiwan is insufficient (COA, 2015b), the minimum amount of corn production was not reduced compared to the productivity in 2015.

$$\sum_j (Y_{corn,j} \times a_{corn,j}) \ge \sum_j Y_{corn,j} \times A_{corn,j} \quad (4)$$

2.3.6. Sugar supply (sugarcane)

The lower self-sufficiency ratio of sugarcane is very similar to that of corn in Taiwan. Therefore, Eq. (4) also represents the concept and formula used for sugarcane.

2.3.7. Water consumption

The available irrigation water volume was subject to irrigation water requirements obtained from the TaiWAP simulation. The simulated rates of change in irrigation water requirements under different climate change scenarios (S_{RCP}) were selected as the rate of decrease in water availability. In the "water conservation policy", the limit on water availability was stricter than in the "food and feed priority policy". Considering the variation in water availability, statistical data for irrigation water availability from 1991 to 2015 were used to determine the irrigation water availability ($W_{i,j}$): (1) the average irrigation water requirement was selected as $W_{i,j}$ in the "food and feed priority policy"; (2) the lower limit of the 95% confidence interval of the data was selected as Wi,j in the "water conservation policy".

$$\sum_j \sum_i (W_{i,j} \times a_{i,j}) \le \sum_j \sum_i [W_{i,j} \times A_{i,j} \times (1\text{-}S_{RCP})] \quad (5)$$

2.3.8. Spatial distribution

From the viewpoint of the agricultural system, it is essential to protect farmland with reference to crop suitability. By adopting the FAO farmland crop suitability evaluation patterns and loading the spatial locations in GIS, digital maps of the crop suitability levels were developed. Crop suitability was evaluated from level 1 through 10, determined spatially according to the physical conditions including elevation, drainage, effective soil depth, soil texture, and soil pH. The resulting maps correspond to the previous results from the Agriculture Land Database Outgiving Center (http://aldoc.coa.gov.tw/aldoc/) crop suitability maps.

The crop spatial distributions in this study were developed using

Table 4
Details of the climate change scenarios used in this study.
Source: IPCC (2007)

Scenario	Radiative Forcing	CO_2-eq Concentration	Pathway shape
RCP2.6	Peak at ~ 3 W/m^2 before 2100, followed by decline	Peak at ~ 490 CO_2-eq before 2100, followed by decline	Peak and decline
RCP4.5	~ 4.5 W/m^2 at stabilization after 2100	~ 650 CO_2-eq (at stabilization after 2100)	Stabilization without overshoot
RCP6.0	~ 6 W/m^2 at stabilization after 2100	~ 850 CO_2-eq (at stabilization after 2100)	Stabilization without overshoot
RCP8.5	> 8.5 W/m^2 in 2100	> ~ 1370 CO_2-eq in 2100	Increasing

ESRI ArcGIS software, version 10.4. The cultivation areas for the three crops (rice, corn, and sugarcane) changed with respect to the climate change scenarios, based on the following processing steps.

1. Each suitability level was selected to create five layers of suitability. The multi-ring buffer tool within ArcGIS was applied to select the polygons with the highest suitability level, which were around the current crop cultivation fields. The distances (200, 400, and 600 m) were determined according to Liu (2011), based on water availability.
2. Finally, the statistical tools within ArcGIS were used to determine the included polygons and their areas.

2.4. Study area: Taiwan

With a population of 2.3 million and an area of only 36,000 km^2, Taiwan has a high population density and high land stress. As an island country, Taiwan is potentially at risk of food, energy, and water insecurity. In the food sector, the rice cultivation area was approximately 146,597 ha in 2015, accounting for approximately 30% of the total agricultural land (COA, 2015a). As the primary staple crop, rice cultivation consumes 7 billion tons of water annually, accounting for over 60% of the total water usage in Taiwan (WRA, 2015). Both sugarcane and corn are also crucial for Taiwan, as economic and feed crops respectively.

With regard to the water sector, despite receiving nearly 2500 mm of precipitation annually, Taiwan continues to suffer from a lack of water resources due to the steep slope and mountainous topography, which makes water storage difficult. Regarding the energy sector, domestic energy production in Taiwan is insufficient to meet domestic demand, making Taiwan highly dependent on energy imports, particularly fossil energy (BOE, 2017a). In 2015, Taiwan used thermal power for about 93.9% of total electricity generation (32.4% from natural gas-fired, 4.1% from oil-fired, 45.4% from coal-fired, and 12.0% from nuclear power), with the remaining generation provided from pumped hydropower (1.2%), and renewable energy (4.8%) (BOE, 2016), which resulted in a heavy environmental burden. According to BOE (2016), energy supply in Taiwan is increasing with an average annual growth ratio of 3.15%. Of the total energy supply in 2015, domestic energy production contributed only 2.16%, while imported energy accounted for the remaining 97.84%. By energy source, the contribution of oil was 48.18%, coal was 29.33%, natural gas was 13.29%, nuclear power was 7.28%, geothermal solar and wind power was 0.16%, solar thermal was 0.08%, and biomass and waste were only 1.39% (as shown in Fig. 2).

Due to potential upcoming energy shortages and the global trend in green energy growth, the Taiwanese government has been aiming for an energy transition in recent years. Based on the "Taiwan 2025 non-nuclear homeland policy" announced in 2016, the government aims to terminate domestic nuclear power production and to increase the renewable energy proportion of the nation's electricity generation to 20% by 2025 (Hong, 2018). The Taiwanese government is focused on reducing pollutant emissions from thermal electric generation, developing new energy sources, and promoting technological innovation regarding alternatives to fossil fuel energy. However, during the transition period of the non-nuclear homeland policy, thermal power may play an even more important role in meeting domestic electricity demand due to the current lack of infrastructure and insufficient technological capability for renewable energy development in Taiwan.

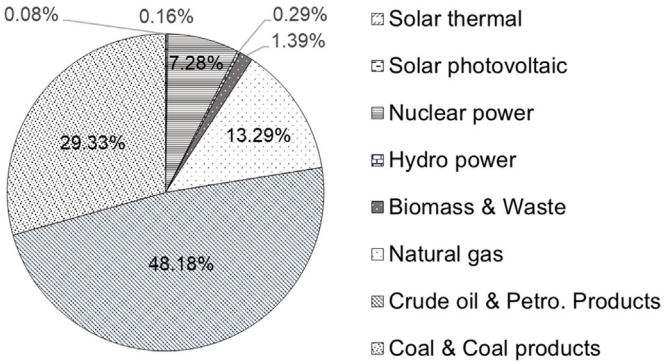


Fig. 2. Energy structure in Taiwan in 2015.
Source: BOE (2016)

Expanding renewable energy is an essential goal of the energy transition. Yue and Huang (2011) identified a high potential for solar energy in Taiwan, which theoretically could have accounted for 16.3% of total domestic electricity consumption in 2009. However, they found that the counties with the highest solar energy potential in central and southern Taiwan (i.e., Yunlin, Chanhua, and Tainan) are also the primary agricultural areas (Yue and Huang, 2011).

2.5. Data

LCIA was implemented through SimaPro software version 8.0 and the Ecoinvent 3.0 database to assess the impacts of all activities in this study. Agricultural information for regional crops was mainly obtained from the Council of Agriculture (COA), Executive Yuan, Taiwan. Meteorological data, including temperature and precipitation, were obtained from the online database of the Central Weather Bureau, Taiwan. Digital maps of spatial crop suitability in Taiwan were sourced from previous studies and online databases. Table 5 lists the data sources and references in this study.

Table 5
Data sources and references.

Data source	Reference
Life cycle inventory	
Rice straw-based bio-coal production	Huang et al. (2013), Syu (2011)
Corn stover-based bioethanol	Lin (2012), Tian et al. (2011)
Sugarcane bagasse-based bioethanol	Chen (2008)
Agricultural information	
Historical cultivation area	COA (2015a, 2015b)
Crop productivity	COA (2015a, 2015b)
Crop characteristics for irrigation water simulation	Chen and Kan (1997)
Meteorological data	TTFRI (2017)
Digital maps of crop suitability	Lin (1996), NLSC (2008)

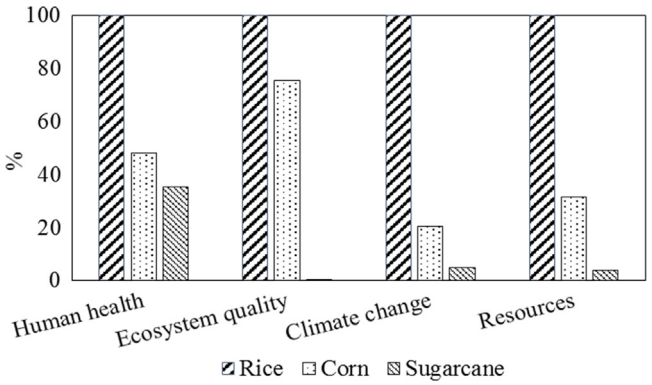


Fig. 3. Damage assessment for the cultivation of rice, corn, and sugarcane.

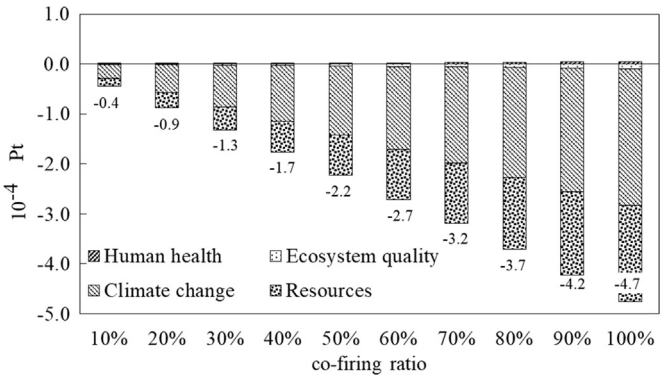


Fig. 5. Reduction in environmental impact when switching from traditional thermal to bio-coal-based electricity generation. The values depict the sum of the four impact categories.

3. Results and discussion

3.1. Result of LCA

The environmental impacts of both bio-coal and cellulosic ethanol were calculated through LCA, with comparisons drawn between traditional energy and bioenergy. The calculated impacts subsequently served as parameters in the optimization model.

3.1.1. Environmental impacts of bioenergy crop cultivation

In the life cycle impact assessment, the damage to the environment was categorized as either: 1. human health; 2. ecosystem quality; 3. climate change; or 4. resources. A comparison of the impacts is presented in percentage form, such that 100% is assigned to the assessment target with the highest environmental impact in each category. Fig. 3 demonstrates that the environmental impact of rice cultivation is higher than the other two crops in all categories.

Tracking back through the production chain, it was found that diesel for operating farm machinery accounted for 16.4% of the total impact, ammonium nitrate for 12.1%, and nitrogen fertilizer for 3.22%. Fig. 4 characterizes the impacts in 15 categories, showing that rice has the highest impact in all categories except carcinogens. The impact of rice cultivation is higher than the other two crops because of crop ammonia emissions and high diesel use for operating farm machinery. The reason that corn has the highest impact in the carcinogen category is the use of the herbicide Atrazine, along with additional nitrogen fertilizer application in corn cultivation.

3.1.2. Bioenergy production

3.1.2.1. Bio-coal. In this study, it is assumed that bio-coal is a major substitute for hard coal for electricity generation. The environmental impact reduction from switching to bio-coal is presented in Fig. 5, based on different co-firing ratios between bio-coal and hard coal. The co-firing ratio is the rate of bio-coal input per kWh electricity, such that 100% represents using bio-coal as the only source for electricity generation. The impacts were weighted using the Impact 2002 + method to generate single values (Pt). Negative Pt values indicate benefits to the environment. Electricity production of 1 kWh was selected as the functional unit. The results show that electricity production with a higher co-firing ratio will have higher environmental benefits due to damage reduction.

Regarding the climate change category, the results indicate that bio-coal production will lead to higher CO_2 emissions than hard coal production. However, the potential climate change impact decreases with increased bio-coal use for electricity production in a co-firing system. The reason for this difference is that CO_2 is absorbed during the crop growth period, which is outside of the assessment boundary for bio-coal production. Previous studies have demonstrated a similar result,

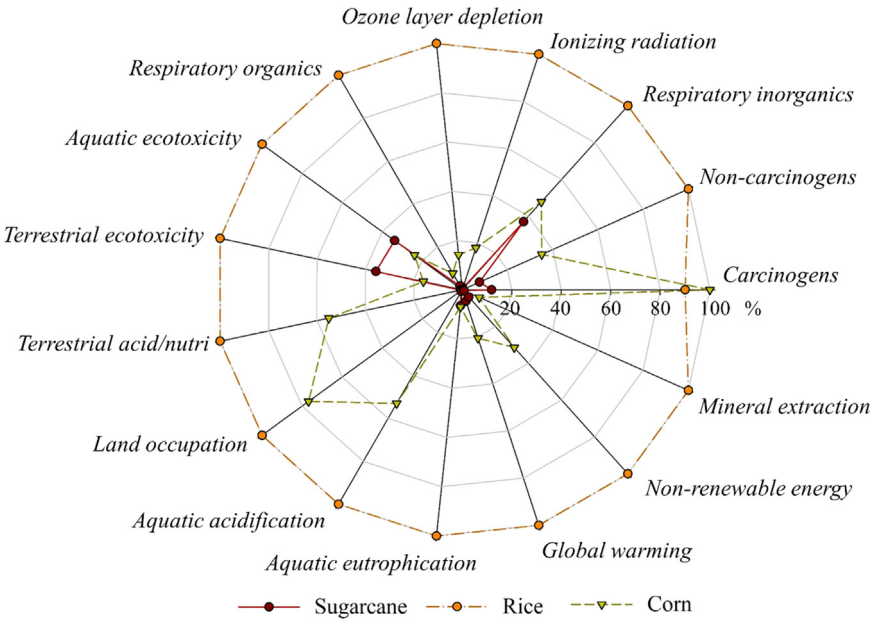


Fig. 4. Characterization of the environmental impact in 15 categories for the three crops.

suggesting that electricity production using bio-coal is beneficial to the environment (Huang et al., 2013; Shafie et al., 2013).

The assessment boundaries for bio-coal production and electricity production were taken from Huang et al. (2013), who indicated that CO_2 absorption during rice growth could offset the CO_2 emissions resulting from the combustion of bio-coal. The reason that CO_2 absorption was not included in the assessment boundary for bio-coal production but was included in the assessment boundary for electricity production hinges on the definition of residue.

In this study, rice straw, a biomass residue, was defined as a waste product when assessing the impact of bio-coal production. Thus, only part of the impact of rice cultivation was attributed to rice straw rather than the whole impact. Because rice absorbs CO_2 during its growth, this benefit was distributed wholly to rice rather than rice straw. However, rice is cultivated not only for food supply but also for bioelectricity production. Hence, the benefit resulting from rice growth was included in the assessment boundary for electricity production.

Furthermore, an expansion of the system boundaries under different co-firing ratios was applied when comparing bio-coal-based electricity production with hard coal-based electricity production. Considering all biomass outputs in the functional unit, instead of only feedstock for bioenergy, can render the system boundary equal among all the alternatives (Luo et al., 2009). Thus, not only agricultural residues but also capital goods were incorporated into the expansive system boundary.

In the current bio-coal system, 1 kWh was selected as the functional unit. Only the amount of hard coal and bio-coal required for co-firing in the thermal power plant were included inside the system boundary. Nevertheless, rice used for food is produced in addition to straw. Regarding this unequal system boundary, all alternatives were expanded by the equivalent amount of food, as shown in Fig. 6. The concept of extending the function unit based on an expansive system boundary is to provide not only the same amount of energy but also the same amount of nutritional value.

In order to supply the same amount of rice as the co-firing system, an expansive system must include rice and its byproduct (i.e., rice straw). Note that rice straw used as a feedstock for bio-coal production in a co-firing system does not provide any nutritional value, so an extra amount of rice was included to equalize the nutritional value to that provided by rice straw in the firing system under the expansive system. The equation below shows the calculation of the expansive system where the left side represents the co-firing system, and the right side represents the firing system.

$$(x+y) \times \text{Heatingvalue}_{\text{rice}} + 1.218\,y \times \text{Heating value}_{\text{rice straw}} = x \times \text{Heatingvalue}_{\text{rice}} + 1.218\,x \times \text{Heating value}_{\text{rice straw}}$$

This equivalence is measured based on the heating value of rice and rice straw, displayed in the following table. When firing without hard coal, the 100% co-firing case, the amount of bio-coal for 1 kWh of electricity generation is produced using 1.411 kg of rice straw, with 1.250 kg of rice produced. Therefore, when firing with hard coal only (i.e., without bio-coal), 2.661 kg of rice and straw needs to be included, which has an additional nutritional value of 45.34 MJ. In conclusion, a new functional unit was created: 1 kWh of electricity plus the nutritional value from 45.34 MJ of rice and straw for food purposes. The new system boundaries were calculated according to the rice and straw heating values in Table 6. The calculation of the new system boundaries for cellulosic ethanol was also based on the heating values presented in Table 6.

Table 6
Heating value for each agricultural product and residue.

	Heating value (MJ/kg)	Reference
Rice	19	Ebeling and Jenkins (1998)
Rice straw	15.3	
Corn	18.8	Bennett et al. (2007)
Corn stover	16.5	
Sugarcane	15.7	Pippo et al. (2014)
Sugarcane bagasse	15.6	

If the aim of crop cultivation is to produce bioenergy, it is necessary to apply the expansive boundary settings outlined in this study to analyze the environmental benefits.

4. Cellulosic ethanol

With regard to gasoline production, a comparison between gasohol blended with cellulosic ethanol and unleaded gasoline is demonstrated. In this study, three kinds of gasohol from two feedstocks (corn stover and sugarcane bagasse), in three distinct blending ratios (E5, E85, and ethanol), are presented. The E5 gasohol is 5% ethanol plus 95% unleaded gasoline in volume, while E85 gasohol is 85% ethanol plus 15% unleaded gasoline in volume.

For ethanol produced from corn stover, gasohol performed better than gasoline among all the four damage categories. For ethanol produced from sugarcane bagasse, the higher the blending ratio, the lower the impacts on both the human health and resources categories. On the contrary, gasoline without ethanol showed lower impacts in the ecosystem quality and climate change categories. The E5 gasohol produced from sugarcane bagasse showed a lower impact in the climate change category compared with using only gasoline, because the reduced sugarcane cultivation is included in the expansive system boundary.

Fig. 7 demonstrates the environmental benefits of gasohol. The results showed that the environmental impact reduction is higher when

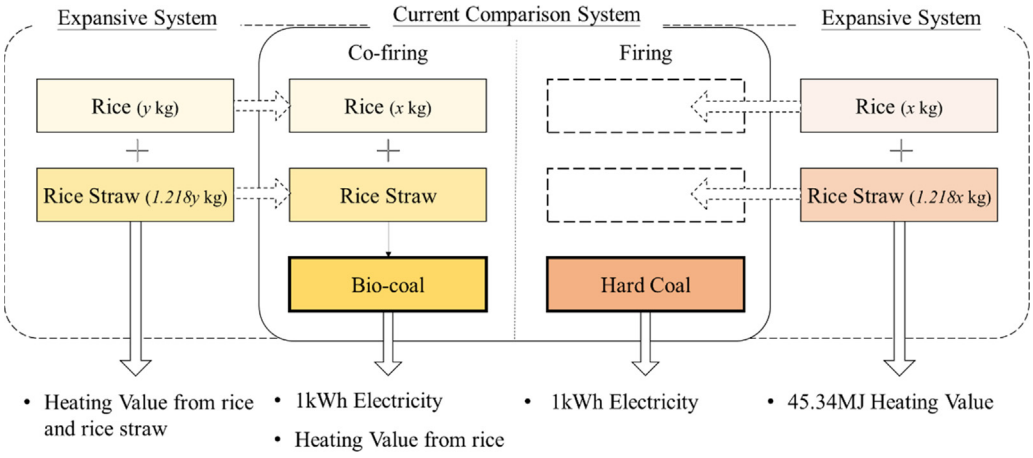


Fig. 6. Expansive system boundary and a new function unit for rice and bio-coal.

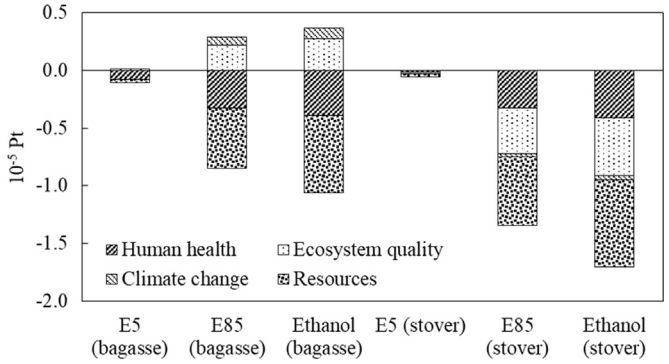


Fig. 7. Reduction in environmental impacts when switching from traditional gasoline to cellulosic ethanol-based gasohol.

the cellulosic ethanol blending ratio is increased for both sugarcane bagasse and corn stover feedstocks. It is worth noting that the sugarcane bagasse-based gasohol showed a better performance than unleaded gasoline only in the climate change and ecosystem quality categories, while the corn stover-based gasohol had a better performance in all four damage categories.

Since little research has conclusively shown that CO_2 absorbed during corn or sugarcane growth can offset CO_2 emissions resulting from the blending process, no adjustment has been applied to the assessment. As per the comparison of electricity production, the expansive boundary was used to compare the environmental impacts of bioenergy and traditional energy. The details of the expansive boundary settings are shown in Figs. 8 and 9.

Our results align with the findings of multiple other studies. One study found that using corn-based ethanol could result in a 44% reduction in GHG emissions compared to using petroleum fuels (Dias de Oliveira et al., 2005). Another study estimated a net energy yield ratio of 1.34 from corn-ethanol yields confirming the potential of corn-based ethanol as a sustainable energy source for transportation (Shapouri et al., 2002). However, other studies have found contrary results. Two studies found that corn-based ethanol production is not a viable solution for displacing petroleum fuels due to the sizable cropland requirement for corn cultivation and the corresponding environmental problems (e.g., soil erosion, groundwater consumption, and volatile compound production) (Dias de Oliveira et al., 2005; Patzek, 2004). While the benefits of cellulosic ethanol production remain under debate, it may nevertheless play a role in solving the energy problem (Hoover and Abraham, 2009).

4.1. Simulation of the irrigation water requirements

Results of the simulation of the irrigation water requirements are shown in Fig. 10. The irrigation water requirements are estimated to decrease under all four climate change scenarios. An average decrease of 3.00% and 2.58% is expected in the central and southern regions, based on RCP2.6, a decrease of 3.78% and 3.06% is expected based on RCP4.5, a 3.26% and 0.66% decrease based on RCP6.0, and a 3.32% and 1.77% decrease based on RCP8.5. The results indicate an obvious decrease in the irrigation water requirements in the post-crop season, particularly the second crop season, compared with the baseline level (1986–2005). This result agrees with Tung and Lien (2000), who found that higher temperatures might shorten the crop growth period, resulting in decreased irrigation water requirements in Taiwan.

4.2. Results of optimization under the two FEW nexus policies

Optimization was implemented through linear programming. The results were compared with the current situation to obtain the ratio of change in cultivation areas. The ratio of change in the cultivation area for each crop, the optimum production of food, energy and water, and the environmental performance, are shown in Table 7.

Under the “food and feed priority policy”, the cultivation area of rice was estimated to remain the same in the northern region across all the scenarios. A slight decrease in area was estimated among all the scenarios in the other regions, except under RCP 6.0 in the central region, while increasing from 1.62% to 4.32% in the southern region. Under the “water conservation policy”, the rice cultivation areas were estimated to decrease slightly under RCP 2.6, RCP 6.0 and RCP 8.5, while remaining the same as the current situation under RCP 4.5 in the northern region, and decreasing much more significantly in the eastern region. The reason for the shift in rice cultivation from the northern and central regions to the southern and the eastern regions is the relatively low water requirement per cultivated area.

With regard to corn cultivation, which produces corn stover for cellulosic ethanol production, the areas in the northern region remained at zero, with all of the corn cultivation concentrated in the southern region under all scenarios, due to the higher impact reduction potential. In addition, there is sufficient land for increasing both rice and corn cultivation in the southern region, due to the arable land released from sugarcane production. Sugarcane production in the southern region accounts for the lowest impact reduction per area due to the low productivity. Under all four scenarios, sugarcane cultivation in the northern region was estimated to increase. Sugarcane cultivation in the eastern region was also estimated to increase in the “water conservation policy” scenario while decreasing in the “food and feed priority policy”.

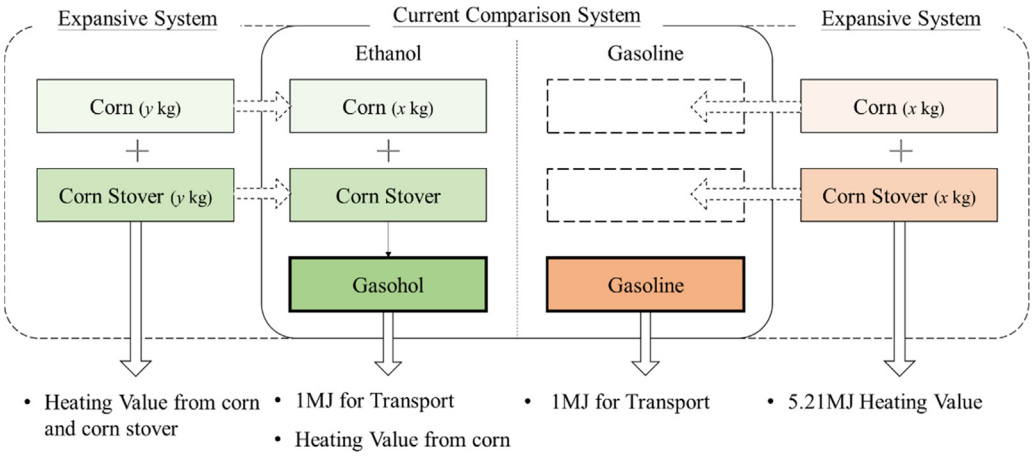


Fig. 8. Expansive system boundary and a new function unit for a corn and gasohol system.

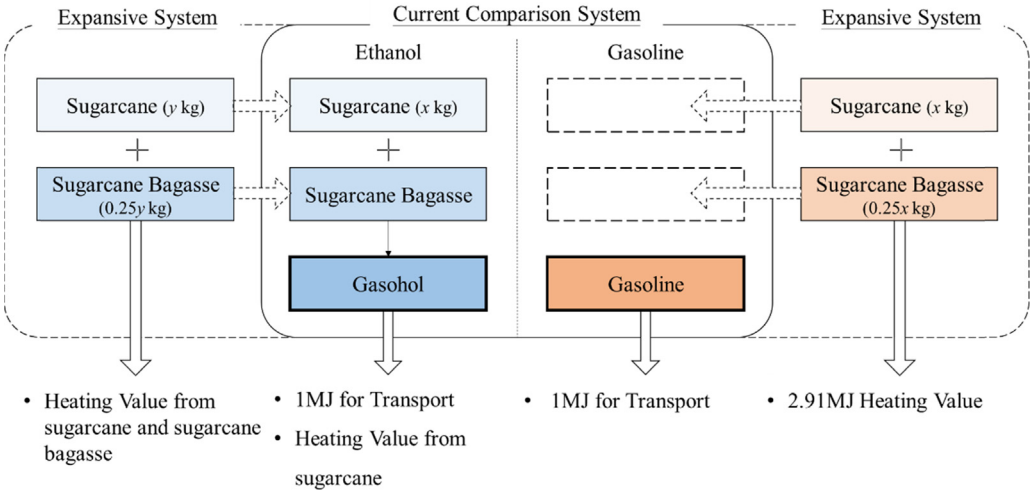


Fig. 9. Expansive system boundary and a new function unit for a sugarcane and gasohol system.

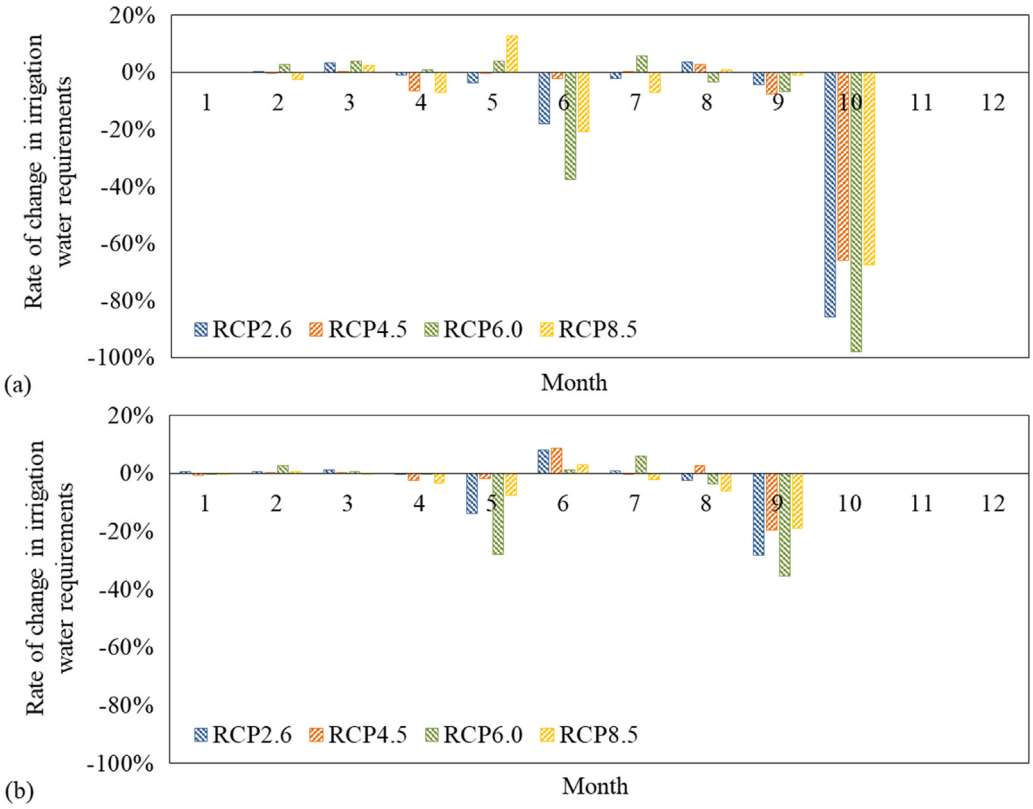


Fig. 10. Simulation of the irrigation water requirements in (a) the central region and (b) the southern region.

Looking at the whole FEW nexus, both the bioenergy supply potential and the food supply potential were higher under the “food and feed priority policy” than the “water conservation policy”. Less water was consumed under the “water conservation policy” than the “food and feed priority policy”. In summary, the “food and feed priority policy” performed better with regard to environmental impact reduction than the “water conservation policy”.

Furthermore, to test the influence of each constraint on the objective function, sensitivity analysis was conducted. The percentage attributed to each constraint (Fig. 11) represents the contribution of the constraint to the objective function, compared with the other factors, when the limit of the constraint is increased by 1%. Fig. 11 shows that arable land in the four regions was the most sensitive factor, especially in the central region. Regarding the constraint on the minimum amount of feed and sugar supply, negative numbers suggested that there would be less impact reduction with an increase in the constraint on minimum feed and sugar supply. For the “food and feed priority policy”, the land resource was the most sensitive factor for environmental impact reduction, since agricultural land can be used to produce feedstock for bioenergy. For the “water conservation policy”, water resource availability was the limiting factor for the development of agricultural residue-based bioenergy.

4.3. Bioenergy development potential

Table 7 also demonstrates the total bioenergy potential in Taiwan.

Table 7
Optimization results for the ratio of change in cultivation area, the FEW nexus, and the environmental performance.

Crop	Region	Food and feed priority				Water conservation			
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Rice	North	0.00%	0.00%	0.00%	0.00%	− 2.72%	0.00%	− 2.12%	− 1.03%
	Central	− 0.52%	− 0.37%	0.32%	− 0.16%	− 1.11%	− 0.28%	− 0.83%	− 0.77%
	South	3.78%	4.32%	1.62%	2.87%	− 1.08%	− 0.71%	− 3.07%	− 3.98%
	East	2.09%	0.86%	2.09%	2.09%	− 5.86%	− 6.67%	− 6.67%	− 3.96%
Corn	North	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Central	− 100%	− 100%	− 100%	− 100%	− 100%	− 100%	− 100%	− 100%
	South	30.58%	30.58%	30.58%	30.58%	30.58%	30.58%	30.58%	30.58%
	East	− 100%	− 100%	− 100%	− 100%	− 100%	− 100%	− 100%	− 100%
Sugarcane	North	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Central	91.94%	89.74%	79.02%	86.49%	101.08%	88.24%	96.80%	95.81%
	South	− 41.97%	− 43.52%	− 35.75%	− 39.35%	− 63.23%	− 58.77%	− 62.89%	− 56.68%
	East	− 100%	14.67%	− 100%	− 100%	639.81%	715.09%	715.09%	463.51%
Food supply	10^3 t	1286	1287	1284	1285	1249	1257	1243	1247
Bioelectricity supply	GWh	1757	1758	1755	1756	1705	1716	1697	1702
Gasohol supply	10^3 KL	124	124	124	124	124	124	124	124
Total water consumption	10^6 m^3	7798	7794	7808	7802	7583	7655	7574	7619
Impact reduction	10^3 Pt	0.526	0.526	0.525	0.525	0.51	0.514	0.508	0.509

The potential annual electricity generation using rice straw-based bio-coal ranges from 1697 to 1758 GWh, which can account for 0.79–0.82% of the total domestic electricity demand. The biomass-electricity generation in 2015 only accounted for 0.09% of total demand, suggesting that there is great potential for bioenergy development. For primary energy supply, the annual bio-coal production potential is approximately 572–593 thousand metric tons, which can account for 4.26–4.42% of the total steam coal consumption by thermal power plants in Taiwan. The annual gasohol production potential totals approximately 124,000 kl, which could account for 1.22% of the domestic demand of the transportation sector in 2015 (BOE, 2017b).

4.4. Spatial optimization of agricultural land

In Taiwan, agricultural land is devoted mainly to cultivating rice, corn, and sugarcane, and is mostly concentrated in the central and southern regions (Fig. 12). The optimum spatial distribution of crops based on the “food and feed priority” and the “water conservation” scenarios indicate that the greatest difference occurs in the central and the southern regions. Under the “food and feed priority policy”, it is recommended that corn cultivation is reduced in the central region. Under the “Water Conservation policy”, a number of changes are recommended to sugarcane cultivation in the central, southern and eastern regions. Sugarcane cultivation is expected to increase in the central region, and decrease in the southern region. The maps of the spatial crop distribution are presented in the Supplementary material (Fig. S4, Fig. S5 and Fig. S6).

5. Implications for energy policy

5.1. Potential of bioenergy generation for food security

Bio-coal-based electricity and cellulosic ethanol-based gasohol generation within the research boundary could potentially satisfy 0.82% and 1.22% of domestic energy demand, respectively. A comparison of these results with the national energy policy in Taiwan and findings from previous studies, which emphasized the analysis of solar energy potential, identified some points deserving of further study regarding food, energy, and water security and the FEW nexus. Yue and Huang (2011) indicated that developing photovoltaic electricity generation and solar water heating has great potential, due to GHG reductions and the land available for installing solar collectors. The Taiwanese government also intends to actively develop solar energy on low productivity agricultural land. However, it is difficult for the government to identify suitable farmland to install solar collectors and PV panels, leading to the risk of food insecurity due to the misuse of farmland for solar energy generation.

In addition, according to AFA (2011) and STPI (2012), the Taiwanese government aims to increase the food self-sufficiency ratio from 32% in 2015 to 40% in 2020. To achieve this goal while developing green energy, bioenergy produced from agricultural residues may play a more important role than solar energy, despite the much higher

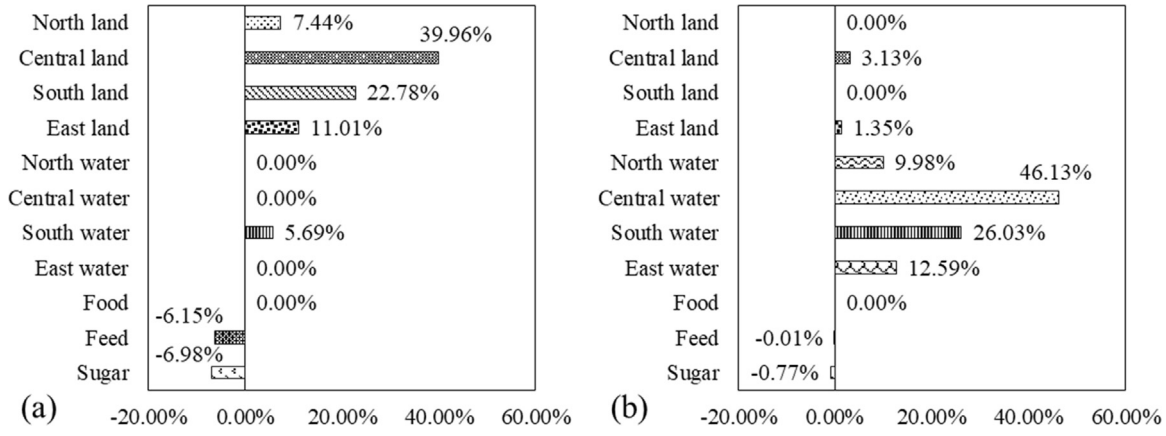


Fig. 11. Sensitivity analysis for each constraint in the optimization model under the RCP 6.0 scenario: (a) food and feed priority and (b) water conservation.

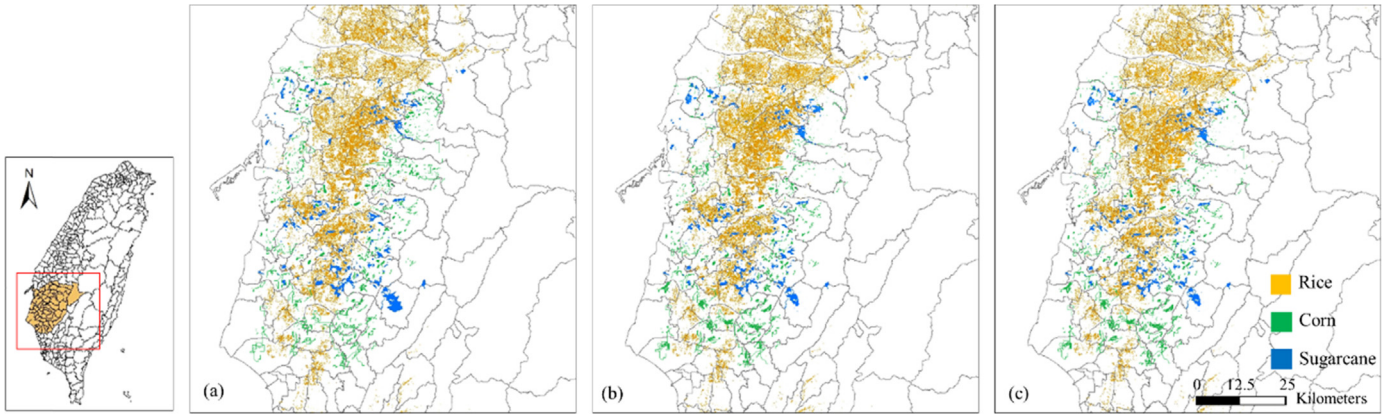


Fig. 12. Spatial distribution of rice, corn, and sugarcane: (a) 2015, (b) food and feed priority under RCP 6.0, and (c) water conservation under RCP 6.0.

potential for solar power in Taiwan. The development of solar energy requires a large amount of land for PV panel installation, which will compete with the limited land resource for the cultivation of food crops. However, the generation of agricultural residue-based bioenergy will not compete with food production.

5.2. Mitigation of the environmental impact of energy generation

The findings of this study indicate that both rice straw-based bio-coal and corn stover- and sugarcane bagasse-based gasohol, are capable of not only mitigating climate change, but also reducing impacts on human health, ecosystems, and resource depletion by replacing hard coal as a feedstock for electricity generation. With respect to climate change mitigation, it is estimated that electricity generation through co-firing with bio-coal will produce 0.208 kg CO_2 equivalent emissions per kWh based on LCA. Taiwan's overall emission factor is 0.521 kg CO_2 equivalent per kWh (TPC, 2015), and the emission factor of coal-fired power generation in Taiwan is 0.726 kg CO_2 equivalent per kWh (TPC, 2017). Bio-coal-based electricity generation offers great potential for GHG reduction, as approximately 40.5 million tons of GHG can be eliminated annually by replacing CO_2-intensive coal-fired generation with the bio-coal co-firing system.

In addition, the replacement of hard coal with bio-coal in coal-fired electricity generation systems can decrease impacts on human health and ecosystem quality due to lower fossil fuel use in bio-coal production than for hard coal mining. Using residues to produce bio-coal also reduces resource depletion, providing a better solution for energy security. Applying gasohol in the transportation sector is more environmentally friendly than using traditional gasoline, particularly corn stover-based gasohol, which can meet 1.22% of the domestic gasoline demand. For a country that depends heavily on imported energy (97.84% of the total energy supply), with high per capita CO_2 emissions, there is potential for the development of bioenergy using agricultural residues to enhance energy security and reduce environmental impacts.

6. Conclusions

The results of LCA indicate that electricity generation using bio-coal produced from the rice straw is very beneficial to the environment. Corn stover- and sugarcane bagasse-based gasohol also performed better than traditional gasoline, with the corn stover-based gasohol having a higher potential for environmental impact reduction.

Since the development of bioenergy is closely related to food or feed and water resources, two hypothetical policies (food and feed priority, and water conservation) were selected to identify environmental benefits and optimize bioenergy yields in Taiwan. Under the “food and feed priority” scenario, higher demand for food and feed supply, with a less stringent constraint on water availability were assumed. The constraint on the area of arable land in the central region was the most sensitive factor in this scenario, as the potential of rice straw-based bio-coal production was the highest. Under the “water conservation” scenario, with a more stringent limit on water availability for the agricultural sector, the constraint on water resources was such an influential factor that the area under rice cultivation had to be reduced. In conclusion, water resource availability is the most important factor influencing food and bioenergy production, as well as the potential for environmental impact reduction.

In terms of renewable energy policy, a comparison between solar energy and bioenergy indicated that solar energy has a higher potential for electricity generation in Taiwan, potentially accounting for 16.3% of the total domestic electricity demand. However, there is a huge controversy over plans for the development of solar energy on farmlands, which is contradictory to the Taiwanese government's policy to increase the food self-sufficiency ratio. Despite the lower potential of bio-coal electricity generation, which can only account for 0.82% of demand, this energy can be produced considering the demand for food supply and limits on water use. Moreover, greater environmental impact reductions can be achieved, with 40.5 million tons of GHG potentially eliminated annually through the use of agricultural residue-based electricity and gasohol. The GHG emissions reduction achieved through the use of solar energy is estimated to be only half this amount.

This study can be regarded as a framework for analyzing the FEW nexus, which not only assesses the feasibility of bioenergy but also considers future circumstances under the influence of climate change. The utilization of GIS tools also enhances the ability to process complex spatial data. The contribution of this study is to provide a new method combining both LCA and climate change simulation modeling with an optimization function to achieve a relatively comprehensive assessment of the FEW nexus. This integrated method can serve as one of the most useful frameworks for future research on the FEW nexus.

Acknowledgements

The authors gratefully acknowledge the financial support from the Ministry of Science and Technology, Taiwan, ROC (MOST-105-2627-M-002-038 and MOST-106-2627-M-002-028).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2018.05.009.

References

AFA, 2011. Report of national food conference, Agriculture and Food Agency, Taiwan. (in

Chinese).
Al-Ansari, T., 2016. Development of the Energy, Water and Food Nexus Systems Model. Imperial College of Science, Technology and Medicine, UK.
Al-Ansari, T., Korre, A., Shah, N., 2014. Integrated modelling of the energy, water and food nexus to enhance the environmental performance of food production systems. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector. 8–10 October 2014. San Francisco.
Alfonso, D., Perpiñá, C., Pérez-Navarro, A., Peñalvo, E., Vargas, C., Cárdenas, R., 2009. Methodology for optimization of distributed biomass resources evaluation, management and final energy use. Biomass Bioenergy 33 (8), 1070–1079.
Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S.J., Yumkella, K.K., 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. Energy Policy 39 (12), 7896–7906.
Bennett, A.S., Bern, C.J., Richard, T.L., Anex, R.P., 2007. Corn grain drying using corn stover combustion and CHP systems. Trans. ASABE 50 (6), 2161–2170.
BOE, 2016. Energy Statistics Handbook. Bureau of Energy, Ministry of Economic Affair, Taiwan.
BOE, 2017a. Guideline on Energy Development. Bureau of Energy, Ministry of Economic Affair, Taiwan.
BOE, 2017b. Energy Statistical Annual Reports. Bureau of Energy, Ministry of Economic Affair, Taiwan.
Brennan, L., Owende, P., 2010. Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. Renew. Sustain. Energy Rev. 14 (2), 557–577.
Callesen, I., Grohnheit, P.E., Østergård, H., 2010. Optimization of bioenergy yield from cultivated land in Denmark. Biomass Bioenergy 34 (9), 1348–1362.
Chen, C.C., McCarl, B.A., Chang, C.C., 2011a. Climate change, sea level rise and rice:Global market implications. Clim. Change 91, 211–231.
Chang, C.C., Chen, C.C., McCarl, B.A., 2012. Evaluating the economic impacts of climate change induced sea level rise with possible adaptation strategies on Taiwan agricultural sector. Agric. Econ. 43, 205–214.
Chen, C.T., Kan, C.E., 1997. Estimate of region-wide crop water requirements in Taiwan area. J. Chin. Agric. Eng. 43 (4).
Chen, S.P., 2008. Greenhouse Gas Emissions Induced by Ethanol Fuel Produced from Sugarcane in Taiwan. National Cheng Kung University, Taiwan.
Chen, C.C., McCarl, B., Chang, C.C., Tso, C., 2011b. Evaluation the potential economic impacts of Taiwanese biomass energy production. Biomass. Bioenergy 35 (5), 1693–1701.
Chiang, S.W., Lin, S.S., Cheng, Y.D., Tsai, C.M., 2015. Investigation of the effects of climate change on rice water availability in Taoyuan irrigation area. Taiwan Water Conserv. 63 (4), 12–22.
COA, 2015a. Agricultural Statistics Yearbook. Council of Agriculture, Taiwan.
COA, 2015b. Food Supply & Utilization 2015. Council of Agriculture, Taiwan.
Criqui, P., Mima, S., 2012. European climate—energy security nexus: a model based scenario analysis. Energy Policy 41, 827–842.
Dias de Oliveira, M., Vaughan, B., Rykiel Jr., E., 2005. Ethanol as fuel: energy. carbon dioxide balances, and ecological footprint. Bioscience 55 (7), 593–602.
Ebeling, J.M., Jenkins, B.M., 1998. Physical and Chemical Properties of Biomass Fuels. Society for Engineering in Agricultural, Food, and Biological Systems.
EU, 2009. Directive 2009/28/ec of the European parliament and of the council. Parliament.
FAO, 2009. Global Agriculture Towards 2050. Food and Agriculture Organization of the United Nations.
Gerbens-Leenes, W., Hoekstra, A.Y., van der Meer, T.H., 2009. The water footprint of bioenergy. Proc. Natl. Acad. Sci. USA 106 (25), 10219–10223.
Haase, M., Rösch, C., Ketzer, D., 2016. GIS-based assessment of sustainable crop residue potentials in European regions. Biomass. Bioenergy 86, 156–171.
Hagman, J., Nerentorp, M., Arvidsson, R., Molander, S., 2013. Do biofuels require more water than do fossil fuels? Life cycle-based assessment of jatropha oil production in rural Mozambique. J. Clean. Prod. 53, 176–185.
Hatirli, S.A., Ozkan, B., Fert, C., 2006. Energy inputs and crop yield relationship in greenhouse tomato production. Renew. Energy 31 (4), 427–438.
Hermann, S., Welsch, M., Segerstrom, R.E., Howells, M.I., Young, C., Alfstad, T., Steduto, P., 2012. Climate, land, energy and water (CLEW) interlinkages in Burkina Faso: an analysis of agricultural intensification and bioenergy production. Nat. Resour. Forum 36, 245–262.
Hiloidhari, M., Baruah, D.C., Singh, A., Kataki, S., Medhi, K., Kumari, S., Ramachandra, T.V., Jenkins, B.M., Thakur, I.S., 2017. Emerging role of Geographical Information System (GIS), Life Cycle Assessment (LCA) and spatial LCA (GIS-LCA) in sustainable bioenergy planning. Bioresour. Technol. 242, 218–226.
Holland, J.E., Luck, G.W., Max Finlayson, C., 2015. Threats to food production and water quality in the Murray–Darling Basin of Australia. Ecosyst. Serv. 12, 55–70.
Hong, Y.H., 2018. The economic and environmental impact of non-nuclear policy in Taiwan. Int. J. Adv. Sci. Res. Manag. 3 (1), 1–4.
Hoover, F.A., Abraham, J.P., 2009. A comparison of corn-based ethanol with cellulosic ethanol as replacements for petroleum-based fuels: a review. Int. J. Sustain. Energy 28 (4), 171–182.
Huang, Y.F., Syu, F.S., Chiueh, P.T., Lo, S.L., 2013. Life cycle assessment of biochar co-firing with coal. Bioresour. Technol. 131, 166–171.
IEA, 2011. Technology Roadmap: Biofuels for Transport. Paris.
IEA, 2015. World Energy Outlook 2015. International Energy Agency, Paris.
IPCC, 2007. Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies: technical summary. IPCC Expert meeting report. 19-21 September 2007. Noordwijkerhout, The Netherlands.
IPCC, 2013. Climate Change 2013: The Physical Science Basis. WMO, UNEP.
ISO14040, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization.
ISO14044, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization.
Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebizer, G., Rosenbaum, R., 2003. IMPACT 2002+: a new life cycle impact assessment methodology. Int. J. Life Cycle Assess. 8 (6), 234–330.
Kay, J.E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J.M., Bates, S.C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J.F., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L., Vertenstein, M., 2015. The community earth system model (CESM) large ensemble project: a community resource for studying climate change in the presence of internal climate variability. Bull. Am. Meteorol. Soc. 96 (8), 1333–1349.
Lin, C.Y., Tung, C.P., 2017. Procedure for selecting GCM datasets for climate risk assessment. Terr. Atmos. Ocean. Sci. 28 (1), 43–55.
Lin, X.H., 1996. Establishing the Crops Suitability Evaluation Geographic Information System for Taiwan Farmland. National Chung Hsing University, Taiwan.
Lin, Y.C., Huang, S.L., Budd, W.W., 2013. Assessing the environmental impacts of high-altitude agriculture in Taiwan: A Driver-Pressure-State-Impact- Response (DPSIR) framework and spatial emergy synthesis. Ecol. Indic. 32, 42–50.
Lin, Y.Y., 2012. Life Cycle Assessment and Energy Potential of Residual Biomass. National Taiwan University, Taiwan.
Liu, F.Z., 2011. Location Priority Assessment Study of Farm Fallow Field. Feng Chia University, Taiwan (In Chinese).
Liu, T.M., Tung, C.P., Ke, K.Y., Chuang, L.H., Lin, C.Y., 2009. Application and development of a decision-support system for assessing water shortage and allocation with climate change. Paddy Water Environ. 7 (4), 301–311.
Long, H., Li, X., Wang, H., Jia, J., 2013. Biomass resources and their bioenergy potential estimation: a review. Renew. Sustain. Energy Rev. 26, 344–352.
Luo, L., van der Voet, E., Huppes, G., Udo de Haes, H.A., 2009. Allocation issues in LCA methodology: a case study of corn stover-based fuel ethanol. Int. J. Life Cycle Assess. 14 (6), 529–539.
Martin, G.M., Bellouin, N., Collins, W.J., Culverwell, I.D., Halloran, P.R., Hardiman, S.C., Hinton, T.J., Jones, C.D., McDonald, R.E., McLaren, A.J., O'Connor, F.M., Roberts, M.J., Rodriguez, J.M., Woodward, S., Best, M.J., Brooks, M.E., Brown, A.R., Butchart, N., Dearden, C., Derbyshire, S.H., Dharssi, I., Doutriaux-Boucher, M., Edwards, J.M., Falloon, P.D., Gedney, N., Gray, L.J., Hewitt, H.T., Hobson, M., Huddleston, M.R., Hughes, J., Ineson, S., Ingram, W.J., James, P.M., Johns, T.C., Johnson, C.E., Jones, A., Jones, C.P., Joshi, M.M., Keen, A.B., Liddicoat, S., Lock, A.P., Maidens, A.V., Manners, J.C., Milton, S.F., Rae, J.G.L., Ridley, J.K., Sellar, A., Senior, C.A., Totterdell, I.J., Verhoef, A., Vidale, P.L., Wiltshire, A., 2011. The HadGEM2 family of met office unified model climate configurations. Geosci. Model Dev. 4 (3), 723–757.
Mo, W., Wang, R., Zimmerman, J.B., 2014. Energy–water nexus analysis of enhanced water supply scenarios: a regional comparison of Tampa bay, Florida, and San Diego, California. Environ. Sci. Technol. 48 (10), 5883–5891.
Monforti, F., Bódis, K., Scarlat, N., Dallemand, J.F., 2013. The possible contribution of agricultural crop residues to renewable energy targets in Europe: a spatially explicit study. Renew. Sustain. Energy Rev. 19, 666–677.
Motoshita, M., Ono, Y., Pfister, S., Boulay, A.-M., Berger, M., Nansai, K., Inaba, A., 2014. Consistent characterisation factors at midpoint and endpoint relevant to agricultural water scarcity arising from freshwater consumption. Int. J. Life Cycle Assess. 1–12.
Mountford, H., 2011. Water: The Environmental Outlook to 2050. OECD Global Forum on Environment: Making Water Reform Happen. Paris. 25–26 October 2011.
Murphy, F., McDonnell, K., 2017. Investigation of the potential impact of the Paris Agreement on national mitigation policies and the risk of carbon leakage; an analysis of the Irish bioenergy industry. Energy Policy 104, 80–88.
NLSC, 2008. Land Use Investigation of Taiwan. National Land Surveying and Mapping Center, Taiwan.
OECD, IEA, 2015. Medium-Term Renewable Energy Market Report 2015. Executive Summary, Paris.
Pahlavan, R., Omid, M., Akram, A., 2012. Energy input–output analysis and application of artificial neural networks for predicting greenhouse basil production. Energy 37 (1), 171–176.
Patzek, T.W., 2004. Thermodynamics of the corn-ethanol biofuel cycle. Crit. Rev. Plant Sci. 23 (6), 519–567.
Pfister, S., Bayer, P., Koehler, A., Hellweg, S., 2011. Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. Environ. Sci. Technol. 45 (13), 5761–5768.
Pippo, W., Luengo, C., Alberteris, L., Pino, G., Neto, J., 2014. Energy recovery from sugarcane: study of heating value variations of sugarcane-trash with moisture content during the milling season. Am. J. Biomass. Bioenergy.
Pishgar-Komleh, S.H., Sefeedpari, P., Rafiee, S., 2011. Energy and economic analysis of rice production under different farm levels in Guilan province of Iran. Energy 36 (10), 5824–5831.
Rasheed, R., Khan, N., Yasar, A., Su, Y., Tabinda, A.B., 2016. Design and cost-benefit analysis of a novel anaerobic industrial bioenergy plant in Pakistan. Renew. Energy 90, 242–247.
Ringler, C., Bhaduri, A., Lawford, R., 2013. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5 (6), 617–624.
Safa, M., Samarasinghe, S., 2011. Determination and modelling of energy consumption in wheat production using neural networks: “a case study in Canterbury province, New Zealand”. Energy 36 (8), 5140–5147.
Shafie, S.M., Mahlia, T.M.I., Masjuki, H.H., 2013. Life cycle assessment of rice straw co-firing with coal power generation in Malaysia. Energy 57, 284–294.
Shapouri, H., Duffield, J.A., Wang, M., 2002. The Energy Balance of Corn Ethanol: An

Update. USDA Publication Number AER-814. United States Department of Agriculture.
Siddiqi, A., Anadon, L.D., 2011. The water–energy nexus in Middle East and North Africa. Energy Policy 39 (8), 4529–4540.
Steubing, B., Zah, R., Ludwig, C., 2012. Heat, electricity, or transportation? The optimal use of residual and waste biomass in Europe from an environmental perspective. Environ. Sci. Technol. 46 (1), 164–171.
STPI, 2012. 2012 Science and Technology Yearbook. Science & Technology Policy Research and Information Center, Taiwan (in Chinese).
Syu, F.S., 2011. Life Cycle Assessment of Producing Biocoal From Rice Straw Via Torrefaction. National Taiwan University, Taiwan (in Chinese).
Tian, W., Liao, C., Li, L., Zhao, D., 2011. Life cycle assessment of energy consumption and greenhouse gas emissions of cellulosic ethanol from corn stover. Chin. J. Biotechnol. 27 (3), 516–525.
TPC, 2015. Taiwan Power Company sustainability Report 2015. Taiwan Power Company, Taiwan.
TPC, 2017. Information disclosure for environment issue Taiwan Power Company, Taiwan. Website 〈http://www.taipower.com.tw/content/new_info/new_info-e14.aspx?LinkID=15〉 (in Chinese).
Tsai, W.T., 2014. Potential analysis of common crop residues for bioenergy sources in Taiwan. Energy Sources Part B 9, 32–38.
TTFRI, 2017. Data Bank of Atmospheric & Hydrologic Research. Taiwan Typhoon and Flood Research Institute.
Tung, C.P., Lien, W.Y., 2000. The influence of climate change on irrigation water requirements. J. Chin. Agric. Eng. 46 (1), 57–68 (In Chinese).
Tung, C.P., Liu, T.M., Chen, S.W., Ke, K.Y., Li, M.H., 2014. Carrying capacity and sustainability appraisals on regional water supply systems under climate change. Br. J. Environ. Clim. Change 4 (1), 27–44.
Tung, C.P., Liu, T.M., Li, M.H., Hong, N.M., Sung, R.T., Lin, C.Y., Tsao, J.H., 2013. The study of integrated assessment of regional water supply capacity under climate change. Taiwan Water Conserv. 61 (3), 1–13 (In Chinese).
Tuong, P., Bouman, B., Mortimer, M., 2005. More rice, less water—integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. Plant Prod. Sci. 8 (3), 231–241.
Wang, H.-F., Sung, M.-P., Hsu, H.-W., 2016. Complementarity and substitution of renewable energy in target year energy supply-mix plannin–in the case of Taiwan. Energy Policy 90, 172–182.
WRA, 2015. 2015 Consuming Water Statistics Annual Report. Water Resource Agency, Ministry of Economic Affair, Taiwan.
Wu, R.S., Li, M.H., Chen, T.Y., 2012. Impact of climate change on paddy rice yields and irrigation water requirement in Taoyuan. Taiwan Water Conserv. 60 (4), 11–25.
Yue, C.D., Huang, G.R., 2011. An evaluation of domestic solar energy potential in Taiwan incorporating land use analysis. Energy Policy 39 (12), 7988–8002.